Wrist-worn Haptic Design for 3D Perception of the Surrounding Airflow in Virtual Reality*

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Abstract

This study proposed a wrist-worn device that displays 3-dimensional (3D) environmental airflow information during Virtual Reality (VR) experience by controlling the rotation of air outlets using servo motors and providing physical airflow using air pumps. Instead of air resistance as the consequence of strong airflow, we focused on reflecting the natural existence of the airflow itself, while maintaining the advantages of wearable devices including being lightweight and convenient to set up. We designed VR scenes to record users' perception accuracy of airflow in different directions and their level of confidence, and evaluated through a within-subject experiment. Based on the results, we discussed the methods for future advancement of haptic perception as well as possible VR application scenarios.

Keywords

Virtual Reality, Haptics, Wearable Design, Airflow Sensation

1. Introduction

To address the lack of real-time haptic perception of VR experience, researchers have presented multiple approaches for simulating wind using air jets and propellers. Since the airflow is generally produced during the player's two-degree-of-freedom (2-DoF) movements and three-degree-of-freedom (3-DoF) rotation, or the use of hand-held tools, most studies paid attention to the creation of instant two-dimensional (2D) directional force on the player's body as the effect of airflow and air pressure.

In this study, we aim to convey the information of continuous 3D airflow in the virtual surrounding environment to the user, through a small and lightweight device that makes a localized body area come into contact with physically generated airflow. Therefore, we proposed a wearable device (Fig. 1 (a)) that allows users to be physically aware of the presence of the wind from specific directions by the tactile perception on the skin surface around the wrist without checking any visual data or auditory cues.

By conducting a within-subject user experiment, we evaluated if users were able to understand the wind direction correctly and confidently through the haptic device.

APMAR'24: The 16th Asia-Pacific Workshop on Mixed and Augmented Reality, Nov. 29-30, 2024, Kyoto, Japan

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2. Related Work

Due to limited configurations of current commercial VR devices, they cannot provide real-time and lifelike haptic feedback along with the change of visual scene. Thereby, approaches have been investigated to physically augment users' feeling of motion and wind [1].

2.1. Airflow-based Force Feedback

Researchers have installed air jets [2, 3] and ducted fans [4] on the head-mounted display (HMD) and combine air propulsion forces from multiple directions to drive the head's offset, aiming for supporting 2-DoF lateral acceleration and 3-DoF rotation. They have proved the effectiveness of presenting air propulsion on physical devices to simulate air resistance in VR as the consequence of the virtual body's movements. On the other hand, Yu et al. [5] have proposed the design of a 360° vibrotactile headband to provide directional cues, which is helpful in indirectly indicating the airflow direction. So far, these studies have primarily focused on actuating the head to address the lack of tactile perception during the high-speed activities in the virtual world, and successfully promote the immersion of VR systems. However, lots of people experienced discomfort such as dizziness and nausea when using VR headsets due to receiving conflicting visual and body movement information [6, 7]. Considering that environmental airflow dynamics are largely independent of human activities, the simulation of environmental airflow on a HMD while participants engage in autonomous movement may result in inconsistencies between visual stimuli and head-driven haptic stimuli. This condition could similarly cause discomfort because of VR sickness and view deflection.

Applying the common approach for head actuation,

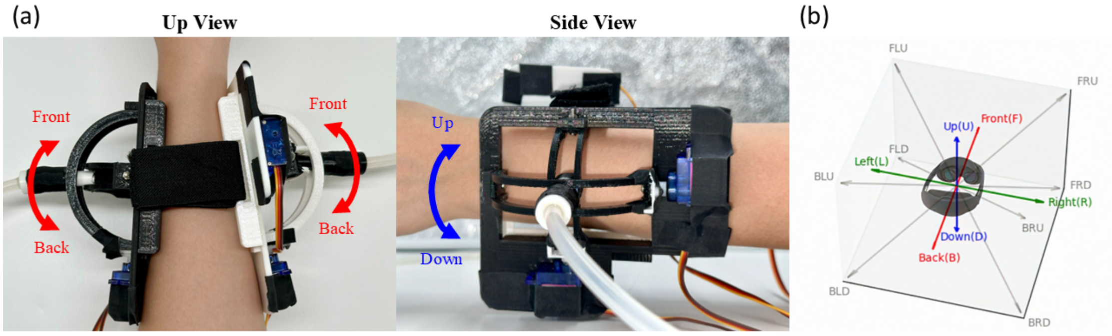

Figure 1: (a) Up View and Side View of the designed Wearable Haptic Device. (b) 14 directions originating from VR headset.

the air propulsion has been achieved through air jets [8, 9] or propellers [10, 11, 12] attached to handheld controllers, yet confining hands to the grabbing posture and limiting natural movements. A handheld tool will become an obstacle instead of an aid if users are expected to freely manipulate control interfaces or objects while perceiving ambient airflow, such as pushing buttons or holding sticks with hands and fingers. The wrist-worn AirGlove [13] and Wind-blaster [14] have proved the feasibility of applying thrust force of varying magnitudes and from different directions on the hand, at the same time enabling flexible hand movements and rotations. Whether handheld or wrist-worn devices, their primary purpose is the exertion of force on the human body during movements or impacts involving individuals or objects, regardless of any hindrance of manual dexterity.

2.2. Wind Sensation

The studies above took advantage of instant generation of airflow and air propulsion force to reflect the impact of human virtual activities, while our research is focusing on continuous existence of airflow for human perception of the virtual environment. Similarly, Ito et al. [15] positioned two fans at the front and back of the VR user to produce actual wind in the environment, whereas as the support of airflow variation it had limited presentation because of the fixed location and orientation. FaceHaptics [16] included wind sensing as part of an integrated movable haptic system, making user perception more spatialized. However, it has the same drawback as other head-worn devices, which is a large system weight that affects head movements and possibly causes physiological discomfort. Moreover, Jaeyeon Lee and Geehyuk Lee [17] paid attention to haptic stimuli at different locations throughout the full body, and resolved the concern through a lightweight and contactless wearable display. They proposed that displaying 2D airflow patterns has comparable effectiveness to vibrotactile patterns in terms of information transfer, which increases the possibility of demonstrating 3D surrounding environment by airflow-based feedback. Hence, our goal is to retain the benefit of wearable design while achieving the presentation of 3D airflow patterns for VR users.

3. System Implementation

3.1. Wearable Haptic Device

To make sure that airflow from 3-DoF directions can make contact with the skin surface, the haptic device has to be worn in a body location that is not limited to a single 2D plane. Among the body parts that have both dorsal and ventral side, the wrist has the highest sensitivity for airflow recognition [17]. Therefore, we chose the wrist as the designated wearable body location for our design.

The device (Fig. 1 (a)) consists of two identical direction control systems, which are composed of 3D-printed components and connected by 3cm wide elastic bands. Each system faces the wrist from the left or right side and contains two micro servo motors (SG92R), which respectively control the orientation of an air outlet in the up-down and front-back directions. Each air outlet is remotely connected to a 12V air pump (AP520B-120) via an air tube (6mm outer diameter, 3mm inner diameter). Both two air pumps are supported by a 12V battery as a power resource, and their open/close status is controlled by a motor driver (DRV8835).

The motor driver and four servo motors are all connected to and controlled by a Arduino UNO microcontroller board. Each servo motor has a degree of freedom of 160 degrees. Therefore, airflow from Up, Down, Front, and Back directions is provided by two air outlets simultaneously, while airflow from other directions is managed by the corresponding left or right direction control system. When airflow comes from an upward angle, the air outlet is oriented upward, allowing the airflow to contact the upper side of the wrist skin; vice versa. Simi-

Given Direction \ Indicated Direction	Front	Back	Left	Right	Up	Down	FLU	FRU	FLD	FRD	BLU	BRU	BLD	BRD	Average Level of Confidence
Front	56.25%	0.00%	0.00%	6.25%	6.25%	6.25%	12.50%	0.00%	6.25%	6.25%	0.00%	0.00%	0.00%	0.00%	3.375
Back	37.50%	31.25%	12.50%	0.00%	0.00%	0.00%	0.00%	0.00%	6.25%	0.00%	0.00%	0.00%	6.25%	6.25%	3.25
Left	0.00%	0.00%	43.75%	0.00%	6.25%	0.00%	25.00%	0.00%	12.50%	0.00%	12.50%	0.00%	0.00%	0.00%	3.0625
Right	12.50%	0.00%	0.00%	50.00%	0.00%	0.00%	0.00%	6.25%	0.00%	25.00%	0.00%	6.25%	0.00%	0.00%	3.4375
Up	0.00%	12.50%	6.25%	0.00%	18.75%	6.25%	25.00%	6.25%	0.00%	6.25%	0.00%	18.75%	0.00%	0.00%	3.625
Down	6.25%	0.00%	0.00%	0.00%	0.00%	25.00%	6.25%	0.00%	25.00%	31.25%	0.00%	0.00%	0.00%	6.25%	3.875
Front-Left-Up (FLU)	6.25%	0.00%	31.25%	0.00%	0.00%	0.00%	50.00%	0.00%	0.00%	0.00%	12.50%	0.00%	0.00%	0.00%	3.25
Front-Right-Up (FRU)	0.00%	12.50%	0.00%	6.25%	6.25%	0.00%	0.00%	31.25%	0.00%	6.25%	0.00%	18.75%	0.00%	18.75%	3.0625
Front-Left-Down (FLD)	0.00%	0.00%	12.50%	0.00%	0.00%	6.25%	18.75%	0.00%	50.00%	0.00%	0.00%	0.00%	12.50%	0.00%	2.9375
Front-Right-Down (FRD)	0.00%	0.00%	0.00%	0.00%	0.00%	6.25%	0.00%	0.00%	0.00%	68.75%	0.00%	0.00%	0.00%	25.00%	3.5625
Back-Left-Up (BLU)	0.00%	0.00%	12.50%	0.00%	0.00%	6.25%	43.75%	0.00%	0.00%	0.00%	37.50%	0.00%	0.00%	0.00%	3.125
Back-Right-Up (BRU)	0.00%	12.50%	0.00%	18.75%	6.25%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	56.25%	0.00%	6.25%	3.375
Back-Left-Down (BLD)	0.00%	0.00%	0.00%	0.00%	6.25%	31.25%	0.00%	0.00%	25.00%	0.00%	6.25%	0.00%	31.25%	0.00%	3
Back-Right-Down (BRD)	0.00%	0.00%	0.00%	12.50%	0.00%	6.25%	0.00%	0.00%	0.00%	37.50%	0.00%	0.00%	0.00%	43.75%	3.5

Figure 2: Confusion matrix of the airflow direction perception study results, and bar chart of participants' average level of confidence regarding their answers for each test direction on a 5-point Likert Scale.

larly, airflow coming from a forward or backward angle is managed in the same manner.

3.2. VR Application

To analyze human recognition of 3D airflow directions, we implemented two VR scenes for 3D data recording: 1) Practice Scene, in which users can feel free to experience the feeling of airflow in different directions; 2) Test Scene, in which users indicate the airflow direction they perceive and answer their level of confidence.

The Practice Scene has 14 "Press me!" buttons positioned in evenly distributed 14 directions originating from the VR headset (Fig. 1 (b)). 6 of them are the positive and negative directions of the X, Y, and Z axes (i.e. +X, -X, +Y, -Y, +Z, -Z), while the other 8 correspond to the diagonal directions of the 8 quadrants formed by these axes. When a "Press me!" button is pressed, the VR system decides the status of air pumps and the rotation angles of servo motors that make the air outlets pointing to the corresponding position on the wrist skin originating from the haptic device, then send data to the haptic device via communication with Arduino.

Following the same mechanism, the Test scene randomly selects one of the 14 directions as a test question and controls the Arduino to present the corresponding airflow, with participants completing 28 tests in which each direction occurs twice. There are 14 black buttons in the same position as the 14 "Press me!" buttons in Practice Scene, which means that the user's answers are also among the 14 directions. After the VR system receives the answer, 5 button choices from "Very Unconfident" to "Very Unconfident" will be shown on the scene to require users' level of confidence.

4. User Study

To evaluate users' ability to understand the direction of 3D airflow by wearing the haptic device, we conducted a within-subject study on perception accuracy and level of confidence.

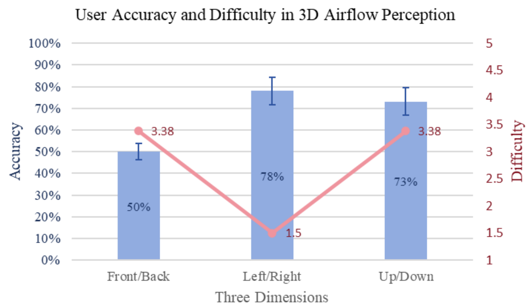

Figure 3: Bar chart of participants' accuracy in perception tests, and line chart of their considered difficulty of perception on a 5-point Likert scale, in terms of three dimensions.

4.1. Study Procedure

Participants sat on a non-swivel chair in a quiet and closed area. Participants wore our haptic device on the wrist of their non-dominant hand, and placed their hand and elbow on 4.5cm stands on the table with palm facing inward. Participants then put on a Meta Quest Pro headset and a noise-canceling earphone with the researcher's help, and hold a VR controller in the dominant hand.

Participants first tried "Press me!" buttons in the Practice Scene without a time limit, and then proceeded to the Test Scene. For each test, participants selected a black button to indicate the perceived airflow direction, selected confidence level and continued to the next test. After completing 28 tests, participants filled out a questionnaire about haptic perception experience, with responses recorded anonymously.

4.2. Participants

We recruited 8 participants, 4 males and 4 females with age 22-28 (mean = 25.3, SD = 2.1). All participants were right-handed and three had prior experience with tactile experiments. 2 participants are familiar with VR. Each participant received 1,500 yen as an honorarium.

4.3. Results

Fig. 2 shows the distribution of airflow perception errors and participants' level of confidence regarding each airflow direction. Participants (P2/5/6) explained that changes in the hit point on their skin helped them determine wind directions. P6 noted that her direction recognition also relied on the skin area where she felt particularly cool. P4/7/8 judged directions referring to the structure of the haptic device and movement of the air outlet around the wrist. Users' average level of confidence is shown to be similar when deciding different airflow directions (mean = 3.32, SD = 0.27). P5 mentioned that her confidence increased when airflow changed along a single dimension, e.g. Front-Right-Up to Back-Right-Up.

The accuracy and considered difficulty of airflow perception in three dimensions are shown in Fig. 3. Participants demonstrated the highest accuracy and the lowest difficulty in answering Left/Right direction among the three dimensions. In contrast, we observed their accuracy in determining Front/Back direction to be much lower compared to the other two dimensions, but participants considered figuring out Up/Down direction to be as difficult as figuring out Front/Back direction. In more detail, P3 described that she first determined the Left/Right side, then a more specific position (i.e. Up/Down and Front/Back on the Left/Right side). Moreover, P1 sometimes felt the airflow was too weak, and P6 suggested that increasing wind strength might make it easier to recognize the wind direction. P3/4 believed they could better understand airflow direction if it were intermittently displayed.

5. Discussion

5.1. Improvement of Airflow Perception

According to the feedback, we analyzed the factors influencing user recognition of airflow direction. Considering that the accuracy of airflow perception from Left/Right, Up/Down and Front/Back directions decreases in turn, we summarized two possible causes: 1) The difference between skin contact areas. Airflow from Left/Right direction touches the wrist dorsal or wrist ventral, similarly airflow from Up/Down direction touches the upper or lower side of the wrist. The Front/Back direction is parallel to the arm, resulting in no specific boundary as reference points, hence users may not be able to clearly define the distinction. 2) The structure of the designed haptic device, involving two parts respectively facing the wrist dorsal and wrist ventral. The actuation of servo motors and movement of the air outlet on each part may amplify the users' tactile sensation of Left/Right direction.

To address current user confusion, we will implement various measures to improve the accuracy of 3D direction recognition. The movement of air outlets could be changed from spherical rotation to 2D movement to create a clearer positional distinction between the front and back ends. To strengthen the intensity of wind perception, the air pumps could be replaced with more powerful alternatives. Regular short pauses could be implemented during the continuous display of airflow to facilitate users' comprehension. A quantitative evaluation could be carried out to assess the precision of haptic display. Additionally, to further investigate the effect of wind contact on various skin areas during VR experience, the device could be worn on multiple different body locations other than the wrist.

5.2. Possible Applications

Compared to placing fans in physical rooms or equipping them with HMD, our wearable device could be more compact and convenient for experiencing the sensation of wind in VR. Our design, which supports continuous 3D reflection of the surrounding, could be particularly suitable for scenarios involving 3-DoF movements at special locations, e.g. high altitudes, forests and caves. In such situations, users are exposed to a 3D space encountering airflow from various dimensions, hence airflow plays an important role in users' environmental cognition. Through future development, we aim to provide more precise directional information to help users better understand environmental changes in such contexts. As a hands-free haptic device, we propose wearing it while engaging in games like battle games that require holding guns and knives, or applications like flight simulators that require mastering steering wheels or control joysticks. Based on these possibilities, we will examine the device's usability within such sample scenarios that involve realistic body movements. Simultaneously, the influence of visual content in HMD on users' recognition of airflow direction will be investigated.

Our device could be used together with plenty of haptic equipment worn in different body areas, such as on the hands [18] or on the back [19]. Their combination may yield synergistic benefits, creating a more comprehensive tactile perception while immersing in the virtual world.

6. Conclusion

In this study, we developed a wrist-worn haptic device that transfers 3D information of the surrounding virtual airflow to VR users by controlling the directions of two air outlets. Through a user study, we analyzed their accuracy of recognizing 3D airflow direction and their corresponding level of confidence. In the future, we will explore various methods to improve the accuracy of airflow recognition, and apply this haptic design to VR scenarios with fluctuating wind conditions.

Acknowledgments

Part of this work was supported by JST PRESTO (Grant Number JPMJPR2134).

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